Effects of Air Pollution on Adult Pulmonary Function

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ABSTRACT. We conducted a study in three representative areas of Beijing to determine respiratory health effects of indoor and outdoor air pollution. In August 1986, we measured the lung function of 1 440 adults who were 40–69 y of age and who had never smoked. Forced vital capacity (FVC) and forced expiratory volume in 1 s ($FEV_{1.0}$) were adjusted for height, sex, and age. Outdoor ambient air pollution measurements from the World Health Organization Global Air Pollution Monitoring Station were very different in the three study areas; the annual mean concentrations of sulfur dioxide (SO_2) in residential, suburban, and industrial areas were 128, 18, and 57 $\mu g/m^3$, respectively, and annual mean concentrations of total suspended particulate matter (TSPM) were 389, 261, and 449 $\mu g/m^3$, respectively. Coal was most frequently used for domestic heating in the residential (92%) and suburban (96%) areas compared with the industrial area (17%). Heating with coal was associated with a reduced $FEV_{1.0}$ (-91 ± 36 ml) and FVC (-84 ± 41 ml). Living in the residential area was associated with an additional reduction in $FEV_{1.0}$ (-69 ± 34 ml) and FVC (-257 ± 37 ml). After we adjusted for age, height, and sex, an inverse linear association was found between ln outdoor SO_2 (or TSPM) concentration and $FEV_{1.0}$ and FVC in subjects who had and had not used coal stove heating. Regression analysis results showed that a per-unit increase in ln SO_2 (TSPM) concentration ($\mu g/m^3$) could result in a 35.6 (131.4) ml reduction in $FEV_{1.0}$ and a 142.2 (478.7) ml reduction in FVC. Not only was coal heating an important risk factor for pulmonary function, but it was a major confounding factor in the analysis of outdoor air pollution effects.

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RESPIRATORY DISEASES are the second leading cause of death in the overall population in China.[1] The magnitude of the problem of respiratory diseases is also well represented by a dozen massive surveys of the prevalence of respiratory diseases.[2] In early 1970, 2 680 957 residents in Shanghai were surveyed for bronchitis. The prevalence rate of chronic bronchitis was 3.0% for all subjects and 12.3% for those who were at least 50 y of age. During the 1970s, a total sample of 2 507 971 residents who were more than 14 y of age were selected in 13 other communities of China. Information on history of chronic bronchitis, emphysema, and chronic cor pulmonale was obtained by special teams appointed by the Ministry of Public Health. The median prevalence rates for chronic bronchitis, emphysema, and chronic cor pulmonale were

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5.6, 1.3, and 0.4%, respectively (highest rates were 13.8, 3.2, and 1.1%, respectively).

Air pollution is thought to be one of the most important risk factors of respiratory diseases.[1] However, to what degree mortality and/or morbidity is attributable to air pollution remains to be estimated. Rapid urbanization and industrialization has contributed to the increasing problem of air pollution in China. Data gathered from air monitoring stations suggest that concentrations of total suspended particulate matter (TSPM) and sulfur dioxide (SO_2) are high nationwide throughout the year. Higher levels of air pollutants have been found in northern cities compared with southern cities, and levels are higher during winter than summer.[3,4] The daily mean concentration of TSPM in 60 cities in China was as high as 660 $\mu g/m^3$.[5] Indoor air pollution caused by coal combustion during cooking and heating, and smoking in crowded households, should not be overlooked as sources of air pollution.

This study investigated the effects of major environmental risk factors on respiratory health in adults in residential, industrial, and suburban (control) areas in Beijing, China. We focused on the relationship between air pollution and pulmonary function among adults who had never smoked. This group of adults was selected because subjects who do not smoke may be more sensitive to airborne contaminants.[6] Also, active smoking would not have been a confounding factor. We initially developed a prediction equation that described the relationship between pulmonary function and several demographic and body size variables, which may have served as important confounders. The model was then expanded to estimate the effects of outdoor air pollution and indoor coal combustion. The impact of cigarette smoking on pulmonary function and its interaction with age, sex, and air pollution will be investigated in subsequent reports.

Methods

Sites selected. Three areas—industrial, residential, and suburban (control)—in Beijing were selected for five reasons: (1) outdoor air pollution monitoring data for these areas have been available since 1981; (2) the resident population was fairly stable; (3) the population was sufficient to ensure that sample sizes of at least 3 600 adults would be available; (4) the population did not include a large number of subjects who had been occupationally exposed to asbestos or silica, etc., thus eliminating important confounders; and (5) the ethnic mix was not too heterogeneous.

Study population. All subjects in the three study areas were selected from 1982 National Census Records. A two-stage random sampling technique was employed. The first stage sample unit was the administrative unit, i.e., JUWEIHUEI or village; at the second stage, it was the subject. Equal numbers of males and females were drawn from each area. Subjects were excluded if they (a) were outside the chosen age range (40 to 69 y of age), (b) were dead, (c) had moved, or (d) were a non-resident or had resided in the three study areas less than 5 y or less than 6 mo/y. Age criteria was based on two assumptions: (1) there is a significant increase in the prevalence of chronic obstructive pulmonary disease in individuals who are 40+ y of age, and (2) it is difficult to obtain a satisfactory pulmonary function test for individuals aged 70+ y. The criteria outlined above accords with available air monitoring data.

Assessment of health effects. A cross-sectional survey was conducted in August 1986. A trained interviewer, who used a modified standardized questionnaire,[7] determined history of chest illnesses, respiratory symptoms, cigarette smoking, occupational exposure, residential history, education level, and type of fuel used for cooking and heating. Pulmonary function measurements were completed in accordance with the guidelines of the American Thoracic Society.[8] Subjects performed vital capacity (VC) and forced vital capacity (FVC) tests on the electric auto spirometer (AS-300, Japan) while in the standing position and with a nose clip. Tests occurred either at the central station or at the subjects' homes. A minimum of three acceptable measurements were performed. The maximum of three measurements was used because it was more reproducible than the mean,[9] and the "best test" was the simplest and most practical result to record.[10] FVC and $FEV_{1.0}$ values were expressed as ATPS because all pulmonary function measurements were made during August and September—times during which indoor temperature was relatively constant.

Air monitoring. The outdoor TSPM and SO_2 (1981–1985) pollution data were obtained from World Health Organization Global Air Monitoring Stations, which were located in the three study areas. Gravimetric and calorimetric pararosaniline methods were used to determine TSPM and SO_2, respectively.[11]

Indoor air pollution. Because indoor coal combustion is the major source of indoor air pollution, and because there was no indoor air monitoring data available in Beijing in 1986, the presence of coal stove heating was used as a proxy for indoor air pollution in this report. Passive exposures to active cigarette smoking at home or at the office were also accounted for.

Procedure. In each area, three survey teams included local interviewers and a core of permanent staff who moved from site to site. Each team was further divided into three groups: (1) an air monitoring group, (2) a questionnaire interview group, and (3) a pulmonary function measurement group. The interviewers trained for 2 wk, during which time they studied the questionnaire and reviewed criteria for adequate testing of pulmonary function. Each subject who was selected received a letter that described and explained the purpose of the study. Local officials and health centers arranged for the subjects to participate in the study at the center station at a convenient time. Home visits were made for those who could not come to the center station. Questionnaire responses were reviewed by each group leader for completeness and consistency. Omitted or ambiguous items were addressed during a re-visit.

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Statistical methods. Dockery et al.[12] indicated that when $FEV_{1.0}$ and FVC measurements were standardized for height (HT), by dividing by HT^2, the decline of lung function with age among never-smokers was described by a simple linear function of age. After repeating the same exploratory procedure with our own data, we found that this method of standardization also eliminated the relationship between height and $FEV_{1.0}$ or FVC in our sample. The same method of standardization for height adjustment was used in the data analysis. The results were made more interpretable by adjusting $FEV_{1.0}/HT^2$ and FVC/HT^2 values to the sex-specific mean height squared, i.e., $FEV_{1.0}/HT^2$ and FVC/HT^2 were multiplied by $(1.67\ m)^2$ for men and $(1.56\ m)^2$ for women.

Several other stages of analysis were performed so that predictive models for pulmonary function could be derived. Bivariate plots of height-adjusted $FEV_{1.0}$ and FVC against age (in 5-y intervals) were constructed by sex. This was done to determine the functional form of pulmonary function with age, sex, and the interaction between sex and age. Several models were then fitted by multiple linear regression. The choice of final predictive models were based on parsimonious parameters, analysis of residuals, and comparison of R^2.

Multiple linear regression techniques were used to estimate the impact of air pollution on pulmonary function. Age, sex, education level, and passive smoking were covariates to be controlled in the analysis of air pollution and coal stove heating effects. The constant term was easier to interpret because age was centered at 55 y in all regression models.

The residual analysis suggested that the variance of the regression model residuals was inconsistent for several covariates. Therefore, ordinary least squares regression provided unbiased estimates of the regression coefficients, but it did not provide valid estimates of their standard errors. When the variance consistency test showed significance differences, robust estimates of the variances of the OLS estimates were calculated using methods described elsewhere.[13]

Results

Sample characteristics. The expected sample was 1 200 persons in each area. However, a total 3 746 subjects were selected and invited to participate, and 3 590 (95.8% of the sample drawn) responded. Those who did not respond included persons who were out of town during the study period or who could not be contacted after three subsequent home visits and those who refused to participate. At the initial examination, 1 572 (43.8%) reported that they had never smoked. Demographic characteristics, passive smoking status, and type of heating used at the home of never-smokers who were in the study are shown in Table 1. The population in the industrial area tended to be younger than in the other two areas. There were obvious disparities in education level, i.e., males were much more educated than females; persons in industrial and residential areas more educated than those in the suburban area. A significant difference in type of heating was found between the industrial area and the other two areas. Central heating was used in at least 80% of the households surveyed in the industrial area, whereas more than 90% of households surveyed in the residential and suburban areas used coal stoves for heating. There were substantial differences in passive smoking status (i.e., males were much more exposed than females), and exposures occurred most frequently

Table 1.—Characteristics of Never-Smokers under Study by Sex, Age, Education Level, Indoor Coal Combustion, and Occupational Exposure

	Men						Women					
	Res.		Sub.		Ind.		Res.		Sub.		Ind.	
	n	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%
Age (y)												
40–44	18	14.0	16	16.0	14	10.5	65	17.5	114	35.3	83	21.6
45–49	25	19.4	20	20.0	30	22.6	72	19.4	67	20.7	111	28.9
50–54	36	27.9	16	16.0	46	34.6	83	22.4	34	10.5	85	22.1
55–59	16	12.4	18	18.0	20	15.0	65	17.5	47	14.6	63	16.4
60–64	20	15.5	19	19.0	17	12.8	49	13.2	35	10.9	29	7.6
65–69	14	10.9	11	11.0	6	4.5	37	10.0	26	8.1	13	3.4
Education												
High school and above	94	72.9	33	33.0	80	60.2	160	43.1	74	22.9	129	33.6
Below high school	35	27.1	67	67.0	53	39.8	211	56.9	249	77.1	255	66.4
Heating												
Coal stove	118	91.5	96	96.0	22	16.5	337	90.8	297	92.0	63	16.4
Central, etc.	11	8.5	4	4.0	111	83.5	34	9.2	26	8.0	321	83.6
Passive smoking												
Yes	72	55.8	29	29.0	95	71.4	167	45.0	87	26.9	205	53.4
No	57	44.2	71	71.0	38	28.6	204	55.0	236	73.1	179	46.6

Notes: Res = residential area, Sub = suburban area, and Ind = industrial area.

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in the industrial area compared with the suburban area, in which exposures were the least frequent.

Air pollution level. China has promulgated its Ambient Air Quality Standards (AAQS), which were revised in 1982.[4] The 5-y (1981–1985) mean concentrations of TSPM and SO_2 in the three study areas are summarized in Table 2. TSPM in all three areas was higher than WHO-recommended limits (Table 2), and it was the highest in the industrial area. The SO_2 concentration was the highest, and well above the AAQS- and WHO-recommended limits, in the residential area. As expected, the suburban area had the lowest concentrations of both major pollutants.

$FEV_{1.0}$ and FVC relationships with age and sex. Sex-specific mean values of height-adjusted $FEV_{1.0}$ and FVC, by age group, are shown in Figures 1 and 2. The height-adjusted values of men were consistently larger than values of women. The average difference was 0.70 l for $FEV_{1.0}$ and 0.87 liters for FVC, which was almost constant over the 40- to 70-y age range. The decline in both height-adjusted $FEV_{1.0}$ and FVC as age increased appeared to be close to linear for both sex groups.

These graphic analyses suggest that height-adjusted $FEV_{1.0}$ and FVC levels varied linearly with age, and that a difference existed between sexes that was independent of age. When this model was fitted by ordinary least squares, the resulting equations were

$$FEV_{1.0} = HT^2 \times [2.668 - 0.031 \times (AGE - 55) - 0.737 \times SEX]/(1.67^2 \text{ for men or } 1.56^2 \text{ for women})$$

and

$$FVC = HT^2 \times [3.365 - 0.035 \times (AGE - 55) - 0.910 \times SEX]/(1.67^2 \text{ for men or } 1.56^2 \text{ for women}).$$

In these equations, $FEV_{1.0}$ and FVC are in liters, age is in y and is centered at 55 y, and sex is 0 for men and 1 for women. The coefficient of determination (R^2) for these prediction equations was 0.466 for $FEV_{1.0}$ and 0.508 for FVC. The standard error of the estimate (root mean squared error) was 0.474 l for $FEV_{1.0}$ and 0.525 l for FVC. We also considered models that included the quadratic age term, but the quadratic age coefficient was not significant for either pulmonary function value.

The height-adjusted $FEV_{1.0}$ and FVC data were fitted, allowing different age coefficients for each sex. No significant differences between regression coefficients for men and women were found for either the $FEV_{1.0}$ or FVC models.

Impact of air pollution and coal stove heating. The predicted height-adjusted lung function values, $FEV_{1.0}$ and FVC, were calculated for each person in the sample. These calculations were completed using a model that included sex and age, and $FEV_{1.0}$ and FVC were subtracted from the observed height-adjusted values to produce pulmonary function residuals. The residual plots, by area, and the presence of coal stoves indicated that reduced $FEV_{1.0}$ and FVC were consistently associated with coal stove heating and with increased air pollution level (Figs. 3 and 4). The slope for $FEV_{1.0}$ for subjects who did not report using coal stove heating was steeper than for subjects who reported using coal stove heating, which suggests that the unexposed subjects may have been more sensitive to airborne contaminants. The effect of coal stove heating on pulmonary function in subjects located in the industrial area was less pronounced than in the other two areas, the major reason being that, since 1978, coal stove heating in many homes had been gradually replaced with central heating systems. The proportion of replacements was highest in the industrial area and lowest in the suburban area. The effects of coal heating in the three areas were inversely associated with the proportion of change in heating system. A stronger association was noted for FVC, which suggested that, after terminating exposure to coal stoves, FVC was less reversible than was $FEV_{1.0}$. The differences in coal stove effects on both $FEV_{1.0}$ and FVC among the three areas and the interaction between coal heating and $\ln(SO_2)$ were tested using a multiple linear regression model. However, none of these were statistically significant.

A multiple regression model of $FEV_{1.0}$ and FVC measurements was used to develop a unified model for sex, age, and air pollution effects. The model included age, sex, educational level, passive smoking, indoor heat type, plus residential areas or their ln SO_2 (or ln TSPM) concentration as regression variables.

As shown in Model 1, on average, a 69-ml and 62-ml decline in $FEV_{1.0}$ and a 257-ml and 177-ml decline in FVC were found in the residential and industrial areas, respectively, compared with the suburban control area

Table 2.—Annual Mean Concentration of TSPM and SO_2 in Residential, Industrial, and Suburban Areas, Beijing, 1981–1985

	Area			AAQS*			WHO†	
	Res.	Ind.	Sub.	I	II	III	Annual	Daily
TSPM ($\mu g/m^3$)	389	449	261	150	300	500‡	60–90	150–230
SO_2 ($\mu g/m^3$)	128	57	18	20	60	100§	40–60	100–150

Notes: Res = residential area, Ind = industrial area, and Sub = suburban area.
*Ambient Air Quality Standard in China.[4]
†WHO guidelines for exposure limits.[11]
‡Daily mean.
§Annual mean.

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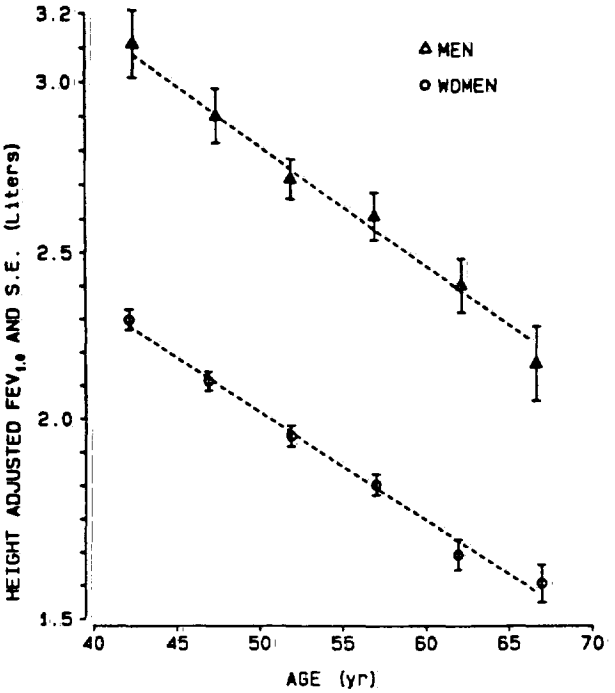

Fig. 1. Comparison of predicted and observed height-adjusted $FEV_{1.0}$ for participants who were never-smokers. The triangles (men)/circles (women) and error bars represent the mean ± standard error of the observed $FEV_{1.0}$ for subjects grouped by 5-y age interval. The dashed line connects the means of the predicted values from the predictive model.

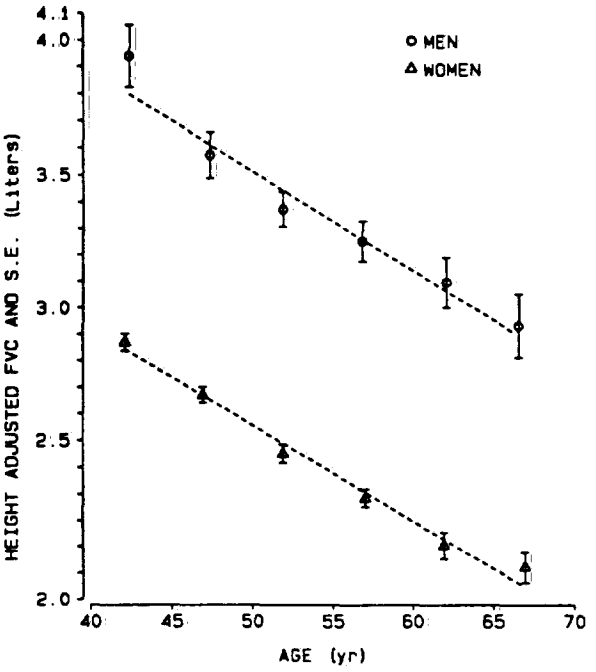

Fig. 2. Comparison of predicted and observed height-adjusted FVC for participants who were never-smokers. The triangles (men), circles (women), and error bars represent the mean ± standard error of the observed FVC for subjects grouped by 5-y age interval. The dashed line connects the means of the predicted values from the predictive model.

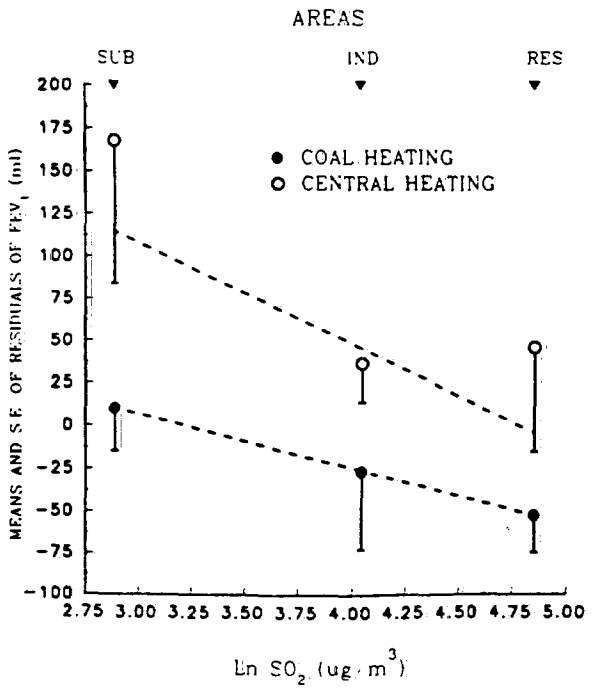

Fig. 3. Mean height-adjusted $FEV_{1.0}$ residuals versus ln sulfur dioxide (SO_2) concentration (μg/m³) in residential, industrial, and suburban areas, by presence of coal stove heating.

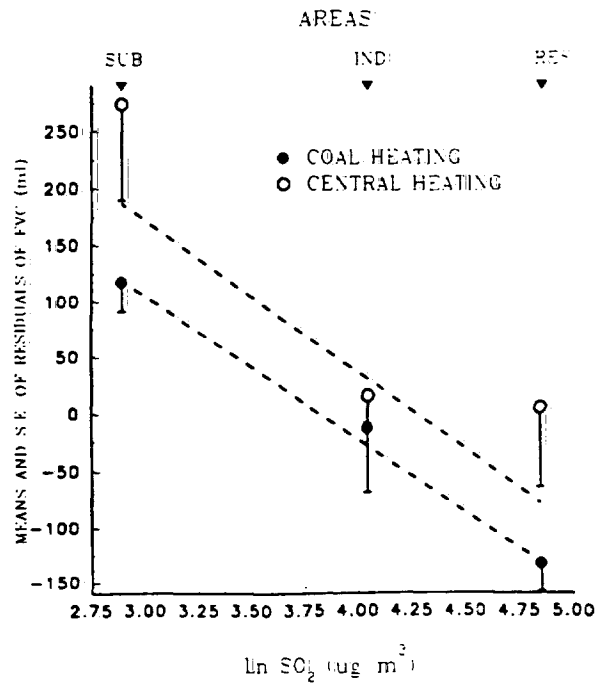

Fig. 4. Mean height-adjusted FVC residuals versus Ln sulfur dioxide (SO_2) concentration (μg/m³) in residential, industrial, and suburban areas, by presence of coal stove heating.

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after adjusting for age, sex, educational level, passive smoking, and indoor heat type. This finding provided an important explanation of why the residential area was associated with the worst pulmonary function. Coal stove heating was found to be independently associated with a 91-ml reduction in $FEV_{1.0}$ and an 84-ml reduction in FVC. In Models 2 and 3, the ln concentration of SO_2 and TSPM in each area replaced the dummy variables. A per ln unit ($\mu g/m^3$) SO_2 increase could result in a 35.6-ml reduction for height-adjusted $FEV_{1.0}$ and a 131.4-ml reduction for FVC. The estimates of a per ln unit ($\mu g/m^3$) TSPM were 4.0 and 3.6 times larger than SO_2 for $FEV_{1.0}$ and FVC, respectively (Table 3). Reduction in FVC was consistently much greater than in $FEV_{1.0}$.

Variance estimation. The standard errors in Table 3 were estimated by the robust methods described previously. Ordinary least squares estimates and robust methods gave identical estimates for regression coefficients but provided different estimates of standard errors and different values for test statistics. The differences between the robust and ordinary least squares estimates of standard errors were small in this data setting. For example, in Model 1, ordinary least squares regression gave standard errors of 40.2, 44.0 and 33.1 for the parameters of coal stove heating, industrial area, and residential area, respectively, which corresponded to 110%, 107%, and 98%, respectively, of the standard errors obtained by robust methods.

Discussion

China is a vast country with significant variations in geographic conditions, socioeconomic development, and industrialization across different regions. As a result, the type, level, and source of air pollution varies enormously from region to region. On the other hand, residential populations are quite stable. All these afford unequalled, wide-scoped natural experimental fields with which to study the health impacts of various types and levels of pollutants.

In this study, three representative areas in Beijing were selected. Beijing is the capital of the People's Republic of China and has a population or more than 10 million. It is also the political, economic, and cultural center of the country. Prior to the 1950s, Beijing was a nonindustrial city. Subsequent to that time, light and heavy industry gradually emerged, e.g., steel plants, petroleum refineries, chemical plants, electric power plants, etc. There are three major sources of air pollution in Beijing: (1) industrial emissions, (2) residential heating and cooking, and (3) natural sources, e.g., wind. Suspended particulate matter and sulfur dioxides are the two major pollutants. Nitrogen oxides have not been considered to be a serious contributor to the environmental problem.

Beijing experiences four distinct seasons. Natural soil dust wind comes from the far north in dry air, especially in winter and spring. A general survey conducted in Beijing showed that natural dust contributed to 40% of the TSPM in winter and 60% in the summer.[14] Even though we specifically examined the association between pulmonary function and outdoor TSPM pollution level in this study, a cautious interpretation should be made. Particle size and composition have been implicated as important determinants of particle toxicity,

Table 3.—Multiple Regression Estimates (Standard Errors) for 1 440 Never-Smoking Adults (Age Centered at 55 y)

	Height-adjusted $FEV_{1.0}$ (ml)*			Height-adjusted FVC (ml)*		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
Constant	2 798.4	2 885.0	3 600.0	3 611.6	3 971.7	6 330.6
	(52.8)	(83.5)	(418.7)	(58.4)	(91.1)	(459.7)
[AGE−55] (y)	−30.4	−30.3	−30.6	−32.6	−32.5	−33.9
	(1.9)	(1.8)	(1.8)	(2.0)	(2.0)	(2.0)
Sex (1 = female)	−734.6	−733.9	−736.3	−907.2	−906.3	−916.5
	(33.6)	(33.6)	(33.6)	(37.4)	(37.5)	(37.6)
Education level (1 = below high school)	−21.6	−23.0	−17.1	−34.5	−36.2	−10.4
	(30.1)	(30.0)	(28.9)	(33.3)	(33.1)	(32.1)
Passive smoking (1 = yes)	−24.4	−25.4	−25.0	−31.9	−33.1	−35.2
	(25.8)	(25.7)	(25.7)	(28.3)	(28.3)	(28.4)
Heating type (1 = coal stove)	−90.9	−75.2	−108.0	−83.6	−64.5	−174.4
	(36.4)	(26.2)	(30.3)	(41.3)	(28.5)	(33.8)
Residential area (1 = yes)	−69.2			−257.1		
	(33.9)			(37.0)		
Industrial area (1 = yes)	−61.5			−176.5		
	(41.1)			(46.2)		
Ln SO_2 ($\mu g/m^3$)		−35.6			−131.4	
		(17.3)			(18.8)	
Ln TSPM ($\mu g/m^3$)			−142.2			−478.7
			(68.6)			(75.4)
R^2†	0.471	0.471	0.471	0.530	0.530	0.526

*Height-adjusted $FEV_{1.0}$ (ml) equals observed $FEV_{1.0}$ divided by height squared times $(1.67\ m)^2$ for men and $(1.56\ m)^2$ for women.
†R^2 is squared correlation between predicted and observed $FEV_{1.0}$ and FVC.

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but TSPM itself did not reveal any distinction in terms of size and composition. The proportion and components of respirable particles varied greatly during different seasons and different areas. Sulfur dioxide emissions, however, resulted primarily from coal combustion. Coal was the dominant energy source in China for many years, and it contributed more than 70% of total energy production.[15] Currently, approximately 18 million tons of coal are burned each year. Nearly half of the coal consumed is burned in the cities, in small boilers and household stoves for heating and cooking. It is burned with low thermal efficiency, no desulfurization, inefficient dust collection, and low smokestacks. The seasonal variations in TSPM and SO_2 concentrations (Figs. 5 and 6) indicated that coal combustion for heating in households was an important source of air pollution in Beijing. However, in the past several decades, the residential area was thought to be a good area to live and that only the industrial area experienced pollution. One of the striking findings in this study was that SO_2 concentration in the residential area was worse than that in the industrial area. A significantly higher proportion (80%) of coal stoves for heating in the residential area compared with the industrial area (30%), and a higher population density in the residential area, may partially explain this finding.

Coal stoves for heating were used as a proxy for indoor air pollution because no data were available on indoor pollution, and coal stoves were thought to be the major source of indoor air pollution. Another advantage of this approach was that the information obtained was highly reliable (i.e., the interviewer was requested to check the central heating facility, if it was reported) and extremely economical because it was collected simultaneously with other information in the questionnaire. Coal stove cooking, however, was not a good index for indoor air pollution exposure because (a) from spring to autumn, doors and windows were kept open in most Beijing households, and the difference in air pollution levels between indoor and outdoor settings would be very small; and (b) in 58% of the households in our sample, the kitchen was separated from the bed/living room during winter (96% during summer). Therefore, even in the winter, during which time all doors and windows are closed, a person, in whose home a coal stove is used for cooking, may not be exposed to cooking coal combustion emissions if he or she does not enter the kitchen. However, during the cold seasons, the coal burning stove for heating was usually placed in the living/bed room where every member in the house was exposed to the air pollutants emitted from it. Therefore, in this report, the coal stove for heating was chosen to represent indoor air pollution exposure. This approach, however, did not afford quantitative information. Also, since 1978, coal stove heating in many homes was gradually replaced with central heating systems. The proportion of replacements was not uniform, i.e., the greatest number of replacements occurred in the industrial area, and the smallest number occurred in the suburban area. The differences in coal effects on $FEV_{1.0}$ and FVC among residents of the three areas indirectly reflected this uneven characteristic. Furthermore, the slope for $FEV_{1.0}$ in subjects who did not report coal stove heating was steeper than that in subjects who reported coal stove heating, which suggested that unexposed subjects were more sensitive to airborne contaminants. However, all of these differences were not statistically significant.

To our knowledge, this is the first community-based respiratory epidemiologic study in China that has used a standardized method. To date, there has been no normal model that describes the association of $FEV_{1.0}$ and FVC with age, sex, and height. It is, therefore, important to develop a basic model for later studies of impor-

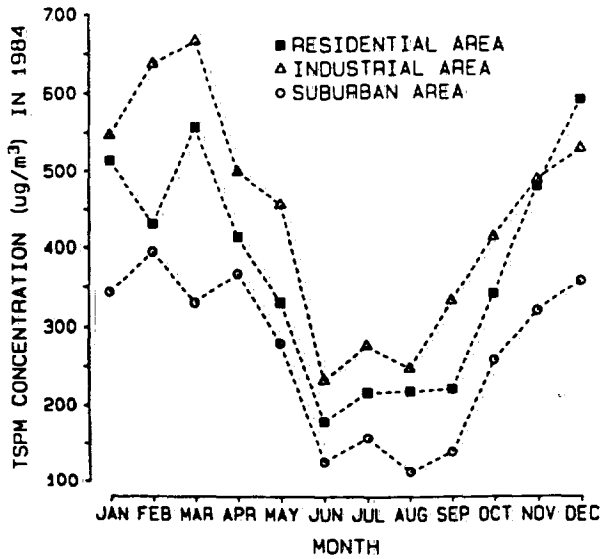

Fig. 5. Seasonal variation of total suspended particulate matter concentration (μg/m³) in residential, industrial, and suburban areas.

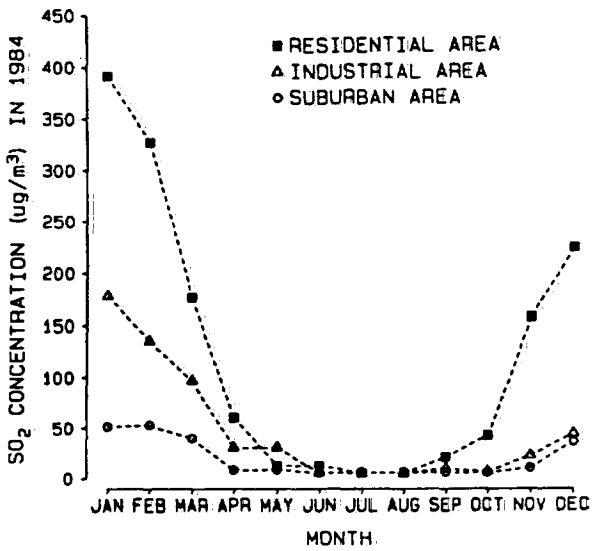

Fig. 6. Seasonal variation of sulfur dioxide (SO_2) concentration (μg/m³) in residential, industrial, and suburban areas.

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tant environmental risk factors in the Chinese population. In 1846, Hutchinson[16] described the relationship between mean vital capacity (VC) and height, weight, and age from measurements obtained from 1 775 healthy men. Since that time, many models for "normal" VC and other measures of pulmonary function were presented. Most models for normal values assumed a simple linear relationship between pulmonary function measurements and height and age. Recently, Dockery et al.[12] showed that nonlinear models were necessary to describe the transition from maximal-obtained lung function in early adult life to lower function in later life. We attempted to develop predicted models for $FEV_{1.0}$ and FVC measured in this sample of 1 440 Chinese adults who were (a) 40 to 70 y of age, (b) residents of Beijing, and (c) never-smokers. Our study confirms that the height-standardized method developed by Dockery et al. well described pulmonary function in this Chinese population. This method had the added advantage that, after standardizing by height squared, it was possible to describe the distribution of pulmonary function values by a two-dimensional display of adjusted pulmonary function values versus age. Our graphic analyses suggest that height-adjusted $FEV_{1.0}$ and FVC levels varied linearly with age (from 40 to 70 y), and that a difference between sexes, independent of age, existed. As a result, a linear model was fitted by least squares to the height-adjusted $FEV_{1.0}$ and FVC. We also considered models that included a quadratic age term, but the quadratic age coefficient was not significant in this age range.

Differences between the sexes in the aging terms of the model were also not significant for both $FEV_{1.0}$ and FVC. This suggested that once aging began, decline in pulmonary function proceeded at the same rate in men as in women, at least in these height-standardized units. Several investigators have noted that the difference in aging between sexes was related to the age at which decline began, and it would be necessary to have separate models for the periods before and after the age at which maximal lung function occurs.[17,18] Our data were limited to age 40 to 70 y; therefore, it would have been inappropriate to extrapolate predictions beyond the age range of this sample. Given that no predictive model for pulmonary function in the Chinese adult population has ever been available and that our study sample was selected randomly, this predictive model may also serve as a reference normal model for Beijing adult residents.

A possible confounding effect of occupational exposure on the regression estimates was also investigated. Information on occupational exposure, collected from modified ATS-DLD questionnaires, included a history of exposure to dust and fumes or gases and specific type, duration, and intensity of exposures. When the occupational exposure variables were added to the regression model, the changes in the coefficients and standard errors were negligible.

Two important findings surfaced from our regression analysis. (1) A per ln unit ($\mu g/m^3$) SO_2 increase could result in a 35.6-ml reduction for height-adjusted $FEV_{1.0}$ and a 131.4-ml reduction for FVC. The estimates of a per ln unit ($\mu g/m^3$) TSPM were 4.0 and 3.6 times larger than SO_2 for $FEV_{1.0}$ and FVC, respectively. The estimated effect should not be interpreted as a unique contribution from a single pollutant because SO_2 and TSPM are strongly correlated. (2) Use of a coal stove for heating was found to be independently associated with a 91-ml reduction in $FEV_{1.0}$ and an 84-ml reduction in FVC. These findings suggested that both indoor and outdoor pollutants had significant effects on pulmonary function in this population. However, the effects found in this study were cross-sectional and cumulative, and a longitudinal study is needed to quantify the association of these pollutants with decline of pulmonary function.

There was a substantial difference in heating type between the industrial area and the other two areas (Table 1). Thus, use of coal stove heating was not only a risk factor for pulmonary function, but it was an important confounding factor to be controlled in the analysis of outdoor air pollution effects. For example, if Model 1 in Table 3 did not include coal stove heating as a controlling variable, the estimated effects of the industrial area would have been 6.2 ml for height-adjusted $FEV_{1.0}$ and −114.2 ml for height-adjusted FVC. Therefore, this model would underestimate the outdoor air pollution effects by more than 60 ml.

As noted previously, the association of outdoor air pollutants with FVC was constantly much stronger than with $FEV_{1.0}$. There was great seasonable variation in air pollutant levels in the areas studied (Figs. 5 and 6). The mean concentration of SO_2 in the residential and industrial areas was as high as 392 and 178 $\mu g/m^3$, respectively, during January, but it decreased to as low as 6 $\mu g/m^3$ during August in the same year. We tested pulmonary function during the period that the SO_2 level was the lowest. Therefore, the results we observed in our study reflected a longterm (i.e., chronic) effect. Fletcher et al.[9] studied a group of working men in London, prospectively over 10 y, and noted that there was a regular seasonal change in $FEV_{1.0}$, i.e., higher values obtained in the two summer surveys than in the winter surveys. Respirable particles could produce inflammatory changes in small airways, which could be reflected in reduced lung function, particularly in reduced $FEV_{1.0}$ (acute or short-term effect). But there is no solid evidence that these changes necessarily proceed to irreversible changes. A greater decrement in FVC than in $FEV_{1.0}$, which was observed in our study, suggested that $FEV_{1.0}$ was more reversible than FVC after exposure to high levels of air pollutants was terminated. Therefore, $FEV_{1.0}$ might be a better health index for short-term (acute) effect, whereas FVC might provide a better health index for long-term (chronic) effects in adults. The study on air pollution effects that was conducted in Berlin, New Hampshire, also maintained that SO_2 and TSPM were much more strongly associated with FVC than with $FEV_{1.0}$.[19]

Studies on the effects of chronic exposure to SO_2 and particulates in adults have been conducted extensively. Areas of higher SO_2 and particulate pollutation have been associated with more respiratory symptoms, an increase in bronchitis, and a lowered $FEV_{1.0}$ level.[20,21] These effects have been seen in nonsmokers but are

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more prominent in smokers. Data from the Berlin, New Hampshire, study indicated that reduction in these pollutants may be followed by some improvement in pulmonary function and an alleviation of symptoms of chronic bronchitis.[22] However, few of the studies provided data on the quantitative relationship between air pollution and adult pulmonary function.

Coal is the dominant energy source in China, and it will be used for many years to come. Coal consumption in cities is estimated to increase 30% by the year 2000. Coal will probably continue to be the major source of air pollution, and it may produce more excess morbidity and mortality from chronic obstructive pulmonary disease and other air pollution-related diseases. These diseases will significantly increase patient loads in hospitals and other health-care facilities, escalate China's health care costs, and reduce industrial and agricultural productivity. Air pollutants emitted from coal combustion in households have exceeded those from industrial resources, and therefore, control of air pollution is of great public health importance in these areas. There is a great need for better technology and better public policy to help prevent the enormous suffering and human loss associated with air pollution.

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